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Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power

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ABSTRACT

This paper presents a comprehensive overview of the life cycle GHG emissions from wind and hydro power generation, based on relevant published studies. Comparisons with conventional fossil, nuclear and other renewable generation systems are also presented, in order to put the GHG emissions of wind and hydro power in perspective.

Studies on GHG emissions from wind and hydro power show large variations in GHG emissions, varying from 0.2 to 152 g CO_2-equivalents per kW h. The main parameters affecting GHG emissions are also discussed in this article, in relation to these variations.

The wide ranging results indicate a need for stricter standardised rules and requirements for life-cycle assessments (LCAs), in order to differentiate between variations due to methodological disparities and those due to real differences in performance of the plants. Since LCAs are resource- and time-intensive, development of generic GHG results for each technology could be an alternative to developing specific data for each plant. This would require the definition of typical parameters for each technology, for example a typical capacity factor for wind power. Such generic data would be useful in documenting GHG emissions from electricity generation for electricity trading purposes.

Contents

1. Introduction

All energy systems emit greenhouse gases (GHGs)[1] and contribute to anthropogenic climate change. Analysis of all the upstream and downstream processes pertaining to a power plant and the associated GHG emissions, e.g. the electricity generation stage, is necessary in order to obtain a complete climate account of power systems. If this is not carried out, the GHG emissions resulting from the various options for electricity generation can be underestimated. For conventional fossil fuel technology, upstream GHG emissions can be as much as 25% of the direct emissions from the power plant. For most renewable energy technologies and nuclear power, upstream and downstream GHG emissions can account for over 90% of cumulative emissions [1].

This paper presents a comprehensive overview of GHG emissions from wind and hydro power generation based on life-cycle assessments (LCAs), showing the variations in GHG emissions within homogeneous power generation technologies. A range of GHG emissions are presented, followed by selected factor analyses.

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[1] To compare GHGs emissions from different sources, the gases are indexed according to their global warming potential (GWP) per unit of weight. GWP is the ability of a GHG to trap heat in the atmosphere relative to an equal amount of carbon dioxide. According to the Intergovernmental Panel on Climate Change (IPCC), over a 100-year time span, carbon dioxide (CO_2) assumes the value of 1. The two other GHGs of importance in these analyses are methane (CH_4) and nitrous oxide (N_2O) which, according to a re-evaluation of the IPCC in 2007, take a value of 25 and 298, respectively.

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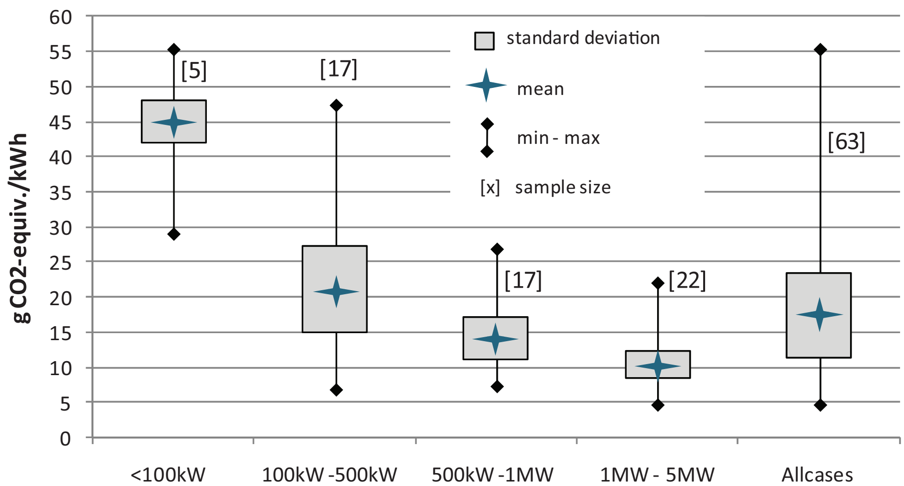

Fig. 1. Summary of life cycle GHG emissions from wind power [7–28] based on turbine size.

The focus is on GHG emissions, despite the fact that climate change is only one of several important environmental impacts when assessing different generation technologies. This work has been carried out as a part of the ongoing research project Energy Trading & Environment 2020 [2], which focuses on GHG emissions as one of the most significant impacts, according to the EU Electricity Directive (2003/54/EG, article 3). This EU Directive requires that suppliers of electricity disclose their electricity portfolio with regard to energy sources and their environmental impact, specifying the emissions of CO_2 and the amount of radioactive waste.

The paper is organised as follows: Section 2: Presentation of different methods for assessing life cycle impacts. Sections 3 and 4: GHG emissions from the generation of wind and hydro power, respectively. Section 5: A comparison of the performance of wind and hydro power in relation to other electricity technologies. Section 6: Discussions and conclusions. Section 7: Recommendations and outlook.

2. Life-cycle assessment methods for electricity generation

The LCAs referenced in this article have been carried out using a variety of methods. A short presentation of these methods is given in the following paragraphs.

Energy analysis is a tool used to assess both direct and indirect energy requirements for the provision of goods and services [3]. The method is based on a bottom-up approach, which means that both the energy requirements of the main production processes and some important contributions from suppliers are assessed in detail.

Process analysis was adopted in the official guidelines for Life Cycle Assessment (LCA), set out by the Society of Environmental Toxicology And Chemistry (SETAC) and is now standardised according to ISO 14 044 [4]. The advantage of this method is the holistic manner in which the value chain of the system is assessed, focusing on all significant processes. The results can be applied in two ways: firstly in optimising the impacts of a product throughout its life cycle and secondly in comparing the impacts of the various alternatives and thus enabling the choice of that which is shown to be most environmentally friendly. However, it is important to ensure that the system boundaries and assumptions are similar when comparing the output from such LCAs.

Input/output analysis (IOA) is another method for assessing the environmental aspects of products and services. IOA divides a product into its economic components (machinery, chemistry, services, etc.) and then calculates an average performance for each economic sector. This average performance is then used as input in order to compute the energy required and the amount of GHGs emitted. The advantage of the IOA is that each input can be easily expressed as an economic value. The life cycle can then be interpreted as a sequence of economic activities. As each activity also has an influence on the monetary value of the product, a relationship between the price and the energy content can be established for each of the economic activities. This approach was inspired by the work of Herendeen [5] among others.

While *process analysis* is a typical bottom-up technique which considers the emissions in particular industrial processes and operations, the IOA method is a statistical top-down approach, which separates the entire economy into distinct sectors. In addition to this, a hybrid approach was developed by Bullard et al. [6], combining the advantages of both methods.

3. Wind power

This section presents the GHG emissions from wind power generation, based on 63 LCAs ([7–27] and [28]), published between1990 and 2010.

Wind power represents a typical intermittent electricity generation technology, as power can be generated only when there is a sufficient level of wind. This means that wind power constantly requires a backup system to compensate for fluctuations. To make a fair comparison between different electricity generation systems, it is important to be aware of limitations such as the intermittent nature of a technology. In order to implement a fair comparison the following approaches can be used: a technology can be analysed in combination with a typical backup system, providing the same reliability as other “stand-alone” systems (e.g. hydro power with reservoir) or, if the assessment does not take into consideration the necessary backup system, it should be made clear that the assessment is at another level than that of other “stand-alone” systems.

The unit of the GHG emissions presented in this paper corresponds to 1 kW h of wind power. Grid losses and infrastructure relating to the grid are excluded from the analyses. The backup power necessary to provide a continuous electricity supply is also excluded from the analyses. Further, it should be noted that while some studies present results for a specific wind turbine (e.g. [12–14]), others present average data for specific wind power projects (many turbines) (e.g. [8]), while yet others are based on average data from several studies (e.g. [25]).

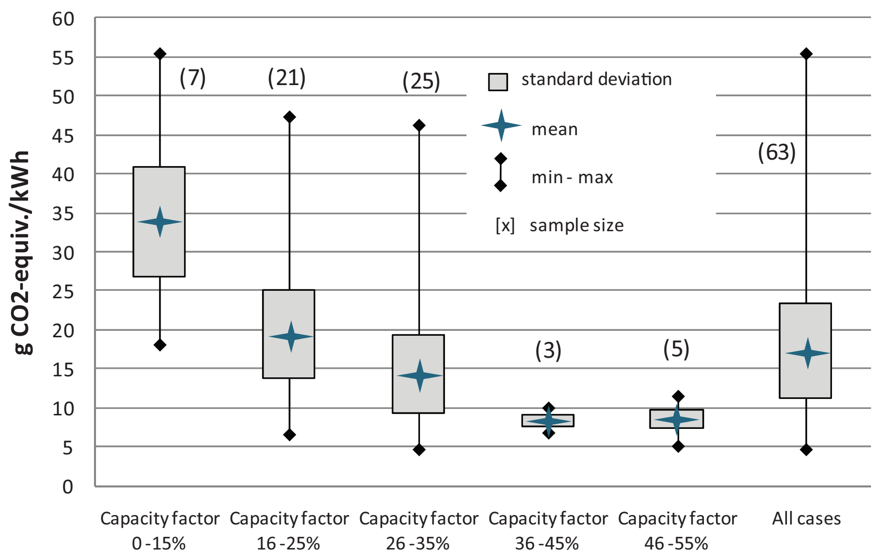

Fig. 2. Summary of life cycle GHG emissions from wind power [7–28] for selected capacity factors (wind conditions).

Fig. 1 shows a summary of the GHG emissions from all the investigated LCAs. It includes the following data: mean value, minimum and maximum values, standard deviation and sample size. These are grouped into four categories depending on turbine size.

The figure shows a large variation in GHG emissions from the wind power plants, varying from 4.6 g [14] to 55.4 [16] g CO_2-equivalents per kW h. The minimum and maximum levels of GHG emissions relate to turbines of 3 MW and 30 kW, respectively. As seen in the figure, the mean value decreases with increasing size, from 45.0 to 10.4 g CO_2-equivalents per kW h. This trend is in line with the results from other studies ([1,10,22,29]). According to Lenzen and Munksgaard [22], such a trend is found to be significant at the 99%-confidence level, confirming that the large variation in GHG emissions from wind turbines reflects economies of scale, with small wind turbines of 1 kW requiring about three times more life-cycle energy per unit power than large wind turbines of 1 MW.

Fig. 2 presents the same data as Fig. 1, but here the data are grouped according to capacity factors, representing varying wind conditions.[2]

The figure shows that the mean value decreases with increased capacity factor, from 33.8 to 8.3 g CO_2-equivalents per kW h. However, the two largest capacity factor groups have approximately equal mean values counting for 8.3 and 8.6 g CO_2-equivalents per kW h. The largest capacity group represents only offshore locations, with larger infrastructures. This could be the reason for the largest capacity factor group having a slightly higher mean value than the second largest group. The extra energy invested in offshore plants can therefore be beneficial, as the performance is comparable to the best onshore sites. It should be noted however that the sample sizes in these two groups are relatively small, having only 3 and 5 cases, respectively. The results show a decrease in GHG emissions in relation to increased capacity factors. These were expected as the capacity factor defines the electricity produced during the life time, and the GHG emissions are expressed by kW h.

An analysis of the assessed GHG emissions from wind power generation, according to analysis type, has also been carried out. This shows that the GHG results appear to increase when changing from process analysis to input–output analysis. This corresponds with the results from a multivariate regression analysis, examining the influence of methodology, scope and technological maturity [22] from which it can be concluded that the results of the energy intensity (and GHG emissions) increase under a change from process to input–output analysis.

Further, the results from the investigated wind power cases clearly show that the infrastructure stage is the life cycle stage contributing most to GHG emissions from wind power generation. It accounts for approximately 90–99% of the total GHG emissions. This life cycle stage includes material production and processing, waste disposal, transport, assembling and installation. Steel production is the activity contributing most to GHG emissions, followed by concrete production. The GHG emissions at the operational stage of wind power are almost negligible in relation to the total.

4. Hydropower

This section sets out the GHG emissions from the generation of hydro power, based on 39 LCAs ([7,16,17,20,30–37]), published between1996 and 2010. The results are presented for 1 kW h hydro generated. With the exception of one study, grid losses and infrastructure related to the grid are excluded from the analyses.

According to Gagnon and van de Vate [30], the two major sources of emissions for hydro power are activities relating to the building of dams, dikes and power stations and the decomposition of biomass from land flooded by the reservoir, producing CO_2 and CH_4 emissions.

Fig. 3 presents the GHG emissions for the studied samples of hydro power categorised into reservoir plants (with and without potential GHG emissions from flooded land) and run-of-river plants.

The figure shows large variations in GHG emissions from these hydro power plants, varying from 0.2 [33] to 152 [16] g CO_2-equivalents per kW h. The large variations in GHG emissions from reservoir hydro power can for the most part be explained by differences in GHG emissions from flooded land, as the standard deviation for this group is 54.5. Recent research [38], shows that this data can be misleading, as the reported emissions may not represent the "net" emissions for which reservoirs are responsible. Most LCAs report "gross" emissions from reservoirs, as measured fluxes over reservoirs. However, there is now consensus that most natural lakes and rivers are also major sources of GHGs, as they return to the atmosphere the carbon flushed into water ways from

[2] The capacity factor is determined [8] as the recorded electricity generation over the year divided by installed capacity and multiplied by 8760 h, so the higher capacity factor, the better wind conditions.

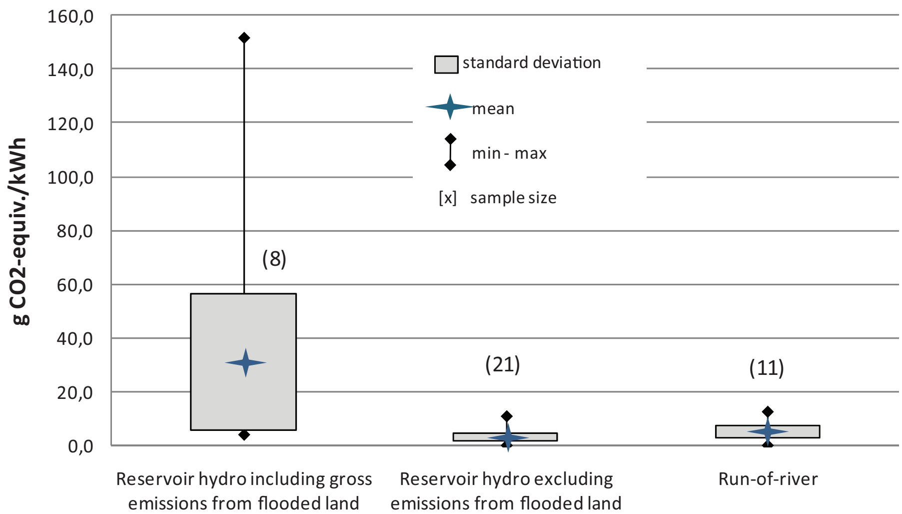

Fig. 3. Summary of life cycle GHG emissions from hydro power [7,16,17,20,30–37]. *Data collected during this work.

surrounding ecosystems. There is ongoing research on this topic, notably the UNESCO/IHA Project on the GHG Status of Freshwater Reservoirs [38]. The aims of the project are to improve understanding of the impact of reservoirs on natural GHG emissions in a river basin, to overcome knowledge gaps and define the “net” emissions from different types of reservoirs.

By excluding flooded land as a GHG emission source from reservoir hydro power, the mean GHG emissions and the standard deviation are both significantly reduced, to approximately 2.9 g CO_2-equivalents per kW h. In addition, the LCAs show that the infrastructure stage contributes from 55.0% to 99.6% of the total GHG emissions when emissions from flooded land are excluded. The major contributing factors to the infrastructure GHG emissions are concrete production and the transportation of rocks in the construction of dams and tunnels.

Run-of-river hydro power generally has no significant area of reservoir [31], and emissions from flooded land are not assessed. The mean GHG emissions are 4.9 g CO_2-equivalents per kW h with a corresponding standard deviation of 4.4. The relative contribution of the infrastructure stage varies from 7% to 99.4% of the total GHG emissions, mainly from building construction and the production of equipment.

5. Wind and hydro power in perspective

In order to put the GHG emissions of wind and hydro power systems in perspective, a comparison with conventional fossil, nuclear and other renewable electricity systems is given in Fig. 4. The figure shows typical minimum and maximum levels of GHG emissions from coal plants, diesel and heavy oil plants, natural gas plants, photovoltaic plants and nuclear plants [10], and compares them with the data collected in this study for wind and hydro power plants.

As seen in the figure, electricity generation using wind and hydro power represents low GHG emissions compared with fossil electricity generation technologies. The figure also shows that these systems can compete with nuclear and photovoltaic power.

6. Discussion and conclusions

The results presented in this article can be assumed to be relatively robust, as the number of LCA studies involved is quite high: 63 wind power cases and 39 hydro power cases. The next table presents a summary of GHG emission variations, principal contributing life cycle stages and principal contributing activities (Table 1).

In the case of reservoir hydro power, more research on GHG emissions from flooded land is required, as this could be the most significant source of emissions. It should be noted that this source is site specific, with large variations, depending on climate, area of flooded land and other factors.

When excluding flooded land as an emission source, the variations in GHG emissions are reduced to between 0.2 g and 11.2 g CO_2-equivalents per kW h, which can possibly be explained by factors such as height of head. An investigation omparing three different data sources ([16,31,33]) has been carried out, documenting various system boundaries for the different life cycle stages. Thus it can be seen that there are challenges in comparing and understanding the variations in such studies.

The GHG emissions from the run-of-river hydro power LCAs show the smallest variation within the investigated technologies. However, deeper investigation is required if the small variations in both the overall GHG emissions and the contribution of the infrastructure stage are to be explained.

With regard to wind power, the main parameters affecting the GHG emissions would appear to be the size of turbines and wind conditions (capacity factor). In addition, waste management in the end-of-life stage, type of material used for the tower, country of steel production and related fuel mix are all parameters affecting the performance of wind power generation. Methodological issues such as the expected life time of the power plant and the life-cycle assessment method would also seem to affect the results.

In the case of both hydro and wind power, more work is required in order to define the parameters that have the greatest impact on the overall performance. This will be the focus of another study which will attempt to define the most representative data relating to these technologies. It is important, however, to bear in mind that GHG emissions from wind and hydro power are comparatively small in relation to fossil electricity generation technologies.

7. Recommendations and outlook

An understanding of the discrepancies in life-cycle assessments is crucial if this tool is to play a role in guiding policy. There appears to be a need for stricter standardisation of the rules

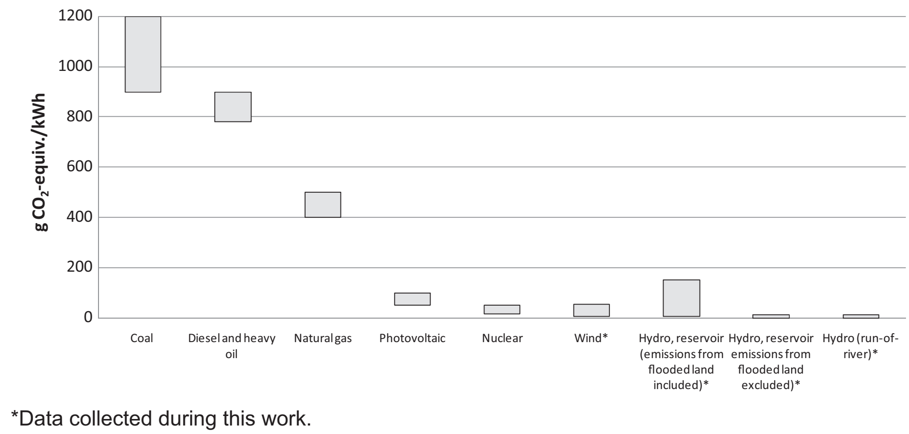

Fig. 4. Life cycle GHG emissions from wind and hydro power compared with other electricity generation systems (based on literature data from [10]).

Table 1
Summary of the findings.

Parameters	Electricity technology		
	Wind power	Reservoir hydropower	Run-of-river hydropower
Number of studies	63	28	11
Variations in GHG emissions [g CO_2-equivalents per kW h generated electricity]	4.6–55.4	4.2–152[a] 0.2–11.2[b]	0.3–13
Principal contributing life cycle stage to the overall GHG emissions	Infrastructure	Inundation of land[a] Infrastructure[b]	Not defined
Variations in infrastructure's contribution to the overall GHG emissions.	90–99%	56–99%[b]	7–99%
Principal contributing activity from infrastructure	Steel production	Construction of dams and tunnels	Building construction and production of equipment

[a] Potential GHG emissions from flooded land are included.
[b] Potential GHG emissions from flooded land are not included.

and requirements when performing LCAs. This would make comparisons between technologies more reliable and would avoid variations due to different methodological assumptions. “Real variations” due to differing performances will always occur, but should not be increased by varying methodological assumptions.

One opportunity for improving such rules is to support the ongoing work on the revision of the Product Category Rules (PCR) [39] for performing Environmental Product Declarations (EPD) [40] for electricity generation. The recommendations coming out of this initiative could include the following: clear system boundaries for the different life cycle stages (which activities to be included where), common methodology for calculating the potential GHG emissions from flooded land and finally, a specific recommended life time for each different electricity technology.

Performing an LCA is resource and time intensive. The development therefore, of generic or “standardised” data for different electricity technologies, could represent an efficient solution for documenting GHG emissions from electricity generation. One application for the use of such generic data could be electricity trading, notably for the calculation of GHG emissions relating to residual electricity mixes in different countries (Electricity Disclosure) and the portfolios of energy suppliers, according to the Electricity Directive. The generic data for GHG emissions could possibly be developed for the different electricity technologies, through assessment of the many varying factors involved.

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